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by

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ADAPTATION OF A TURBINE TEST FACILITY TO HIGH-TEMPERATURE RESEARCH

(ADAPTATION D'UN BANC DE TURBINE AUX RECHERCHES POUR LES HAUTES TEMPERATURES)

by

J. Francois, Y. Le Bot, J. Michard, P. Deguest

AGARD Conference Proceedings No.229, Ankara, September 1977

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Translator

Barbara Crossland

Translation editor

~~E.T. Wedlake~~

EDITOR'S SUMMARY

A facility for research on a high temperature (1800 K) and high pressure (4.5 bar) turbine stage is described. The turbine operates in a realistic engine environment and is comprehensively instrumented to permit wide variation of mainstream and coolant flow parameters.

The development of robust probes for the measurement of turbulence and temperature fluctuations and optical pyrometry techniques is described.

Results of studies of nozzle guide vane heat transfer coefficients, metal temperatures and film cooling efficiency are presented together with rotor blade surface temperature distributions.

The MINOS rig has confirmed the validity of turbine design prediction methods by providing performance data to correlate theory, scale model testing and gas turbine engine testing.

Future work on this rig will aid the design of optimum blade cooling systems and investigate the validity of blade life prediction methods.

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1 INTRODUCTION

Modern turbojet engines are characterised by elevated temperatures, accompanied by elevated turbine inlet pressures, in order to reduce their specific fuel consumption. In parallel, one demands of their components, and particularly of the turbine, higher work output and longer lives[1].

In order to achieve these objectives, it was necessary to develop cooling techniques, firstly by improving internal convection and then by recourse to film cooling.

The increase in pressure levels, which results in an increase in heat transfer, has made the blades more sensitive to fatigue problems. Their behaviour has thus become more and more a local temperature problem and no longer a mean temperature one.

A detailed knowledge of external conditions, heat transfer coefficients and temperatures, is therefore now of prime importance. The influence of the engine environment then becomes significant; pressure heterogeneities, temperature heterogeneities, the level of turbulence, wakes and rotational effects can affect heat transfer coefficients and the efficiency of film cooling.

The output of the turbine installed in an engine can also be greatly affected by the engine environment; coolant discharge from the blades or platforms, leakages, clearances and wakes can degrade it to a marked degree.

For this reason, having developed prediction methods and laboratory model tests in the fields of study concerned, it became apparent that a test method should be conceived which reproduced as closely as possible the environmental conditions of the engine, whilst enabling high quality measurements to be carried out.

The aim is not only to check the performance of the blading and to evaluate its efficiency under conditions close to those of the engine, it is, above all, to characterise these operating conditions in order to understand the influence of the different parameters and to validate the numerical prediction methods.

It is with these objectives in mind that government agencies (Direction des Recherches et Moyens d'Essais, in association with the Direction Technique des Constructions Aéronautiques) have brought an engine company, SNECMA, a research organisation, ONERA, and a specialised test centre, CEPr, into the MINOS project (Montage Inter ONERA-SNECMA).

2 ROLE OF MINOS IN THE STUDY OF HIGH-TEMPERATURE TURBINES

The detailed measurements which are desirable for refined analysis of the performance of the different components of a turbine are generally impossible to obtain on a test-engine, due to their compactness and to the severe environmental conditions encountered (elevated temperature and pressure levels, vibrations). Moreover, the conflicting requirements of different disciplines (aerodynamic, thermal, metallurgical, mechanical) frequently make it impossible to gather results other than those which are too universal to be readily transposed to another type of turbine.

Therefore, the validation of design prediction methods and the estimation of prototype performance, based on the results of laboratory studies, requires the specification of an experimental rig intermediate between static model thermal test rigs, and engines proper. This experimental rig must include sufficiently flexible and comprehensive operational control systems to permit independent variation of the parameters influencing the phenomena to be analysed in an environment comparable with that encountered in engines. Furthermore, its instrumentation system must be sufficiently comprehensive to enable measurements to be made which are as detailed as those available from model test rigs.

MINOS has been defined to meet these objectives. Its place as a test vehicle in the study of high-temperature turbines is described in Table 1. The key position which it occupies in relation to engine testing, to model tests, and to studies on simple rigs designed for fundamental research, is clearly shown in this table. Results obtained using MINOS, should assist in specifying the direction of model test rig programmes and conversely will show the complementary nature of these two types of installation.

3 OBJECTIVES

The general objective of MINOS, which is the study of all the parameters influencing the performance and behaviour of the blades of a cooled turbine will be achieved by means of the following steps:

- verification of satisfactory aerodynamic operation;
- characterisation of the environment: measurement of turbulence level, measurement of temperature distribution, wake analysis;
- study of heat transfer coefficients;
- study of the efficiency of protective films;
- thermal fatigue tests;
- tests on blades capable of withstanding high temperatures;
- study of particular technical problems, platforms, shroud rings, abradable materials ... .

The verification of good aerodynamic operation is important; thermal results cannot be correctly interpreted without a satisfactory knowledge of aerofoil velocity distributions.

The characterisation of the environment will make it possible to evaluate the differences between engines and static test rigs and will be carried out in the different planes of the turbine.

The study of heat transfer coefficients and film cooling effectiveness will be carried out using the same methods of measurement and the same blades for both the static tests and for MINOS. Initially, blades will be tested having simple films at the leading edge, either on the suction surface or on the pressure surface; then combinations of these films will be tried. Both thermal efficiency and variations in heat transfer coefficient due to the presence of film cooling will be determined. The validation of methods of fatigue life prediction will be carried out by cycling the flow of cooling air to the rotor blades; the cooling system will be designed to maintain safe thermal stress levels for this method of operation.

In addition to these objectives has been added the ability to carry out type testing of advanced technology guide-vanes in order to uprate the rig for use at high temperatures.

Finally, since the cooling of the blades is not the only problem resulting from exposure to high temperatures, and since attainment of high work output depends on the control of clearances and leakages, studies of certain technical problems have been added to the programme, for example, platform cooling, thermal protection of casings, and the behaviour of abradable materials.

4 MEASUREMENT TECHNIQUES

In order to achieve the prime objectives, particular attention has been devoted to the specification of the instrumentation.

The test rig is equipped:

- on the one hand with conventional instrumentation designed:
  - to control the temperature of guide-vanes, discs, bearings, casings ...;
  - for the measurement of pressures, temperatures and flow rates in the mainstream, and in the cooling air circuits;
  - for the control of vibration in various parts of the rig;
  - for control of turbine operation at test points.
- on the other hand, the test rig is equipped with measuring instruments, specially developed within the scope of the MINOS programme, which can withstand a gas temperature of 1800 K and which enable measurements to be carried out previously restricted to laboratory studies.

These novel measurements are described below, emphasising, above all, the principle of the technique adopted; moreover, some of the instruments used are the subject of a more detailed presentation elsewhere within the proceedings of this symposium[2].

4.1 Characterisation of the non-steady components of flow

4.1.1 Pressure fluctuations; aerodynamic turbulence

The characterisation of flow turbulence in turbines is difficult because of the fragility of hot-wire probes and the fact that laser anemometry techniques are still too new to be readily applied to industrial type machines.

The use of pressure sensors having a short response time proves to be a suitable alternative. In fact, various comparison tests of the response of non-steady pressure sensors and of hot-wire probes have shown that the stagnation cut-off pressure δp_i and the incremental velocity δV are represented by[3]: $\delta p_i = K \rho V \delta V$, where ρ and V are the density and the mean flow velocity respectively at the point considered.

The constant, K, has a value of 2 for the type of sensor used. Results of spectral analysis, shown in Fig 1, illustrate this relationship between fluctuations of pressure and velocity; the measurements were recorded during flow tests at moderate temperature ($\simeq$ 340 K).

Pressure sensors having short response times have been used on the MINOS test rig to characterise flow turbulence at inlet to the HP nozzle guide vanes.

4.1.2 Flow temperature fluctuations

Flow temperature fluctuations at turbine inlet are measured by means of a fine thermocouple probe ($\phi \simeq 0.1$ mm). The response of the sensor is corrected electronically by considering the time constant of the measuring element, in accordance with the relationship[4]:

$$T(t) = T_s(t) + \frac{\tau dT_s(t)}{dt}$$

where $T_s(t)$ is the uncorrected response of the sensor and τ is the corrected time constant of the junction of the thermocouple. The calculation of τ is based upon the geometry of the junction, and the test conditions[5].

The pass-band of the associated sensor-electronics is of the order of 200 Hz. For markedly higher frequencies, up to 10 kHz for example, only the use of an optical pyrometer, measuring instantaneous gas temperatures, can be envisaged. Such instrumentation adapted to MINOS test conditions, is already under study.

4.2 Analysis of rotor blade wakes

The experimental study of rotor blade wakes is needed for any analysis of local aerodynamic performance. For cooled blades, it is equally interesting to characterise the effect of the injection of films on aerodynamic behaviour. This can be achieved by the study of pressure and velocity profiles in the wakes of the blades.

Hot-wire anemometry is, in principle, well suited to this kind of problem. It has given excellent results during research work on compressors[6], but the fragility of the sensors prohibits its use in turbine tests.

The recent technique of laser anemometry also appears to be a very attractive proposition[7], and its application to turbines can be envisaged in the short term. In this context, one approach to the problem can be made by means of short response time pressure sensors.

The principle of measurement is described in Refs 8 and 9. The main difficulties lie, on the one hand, in the necessary miniaturisation of the sensors so that their diameters are as small as possible in comparison with the breadth of the blade wakes, and, on the other hand, in obtaining a very short response time in order to preserve good definition of the shape of the wakes.

The miniaturised pressure probes developed within the framework of the MINOS programme are water cooled, and are fitted with a sensitive piezoelectric element. The response time is of the order of 1 μs, and satisfactory operation has been verified up to 1800 K.

4.3 Determination of nozzle guide vane heat transfer coefficients

The method used for the measurement of nozzle guide vane heat transfer coefficients is based on an analysis of the rise in temperature of the vanes when the cooling air is shut off (Fig 2). Reconstructing the development of the thermal field in the vane wall

as a function of time, on the basis of local temperature measurements, one can derive the external heat transfer coefficients over the vanes[10]. The analysis is mainly carried out at mid-span; however, thermocouples have also been implanted close to the platforms, in order to ascertain the effect of secondary flows on heat transfer.

4.4 Measuring rotor blade surface temperatures - optical pyrometry

The measurement of local temperatures on rotor blades by means of thermocouples is often used on industrial test rigs. In order to obtain precise recordings of blade behaviour, it is necessary to have a large number of thermocouples; the transmission of signals emitted by the thermocouples is a complex and delicate problem.

In the case of the MINOS test rig, the possibility of carrying out such measurements has been considered.

However, this technique appears to be inadequate for purposes of establishing a detailed blade surface temperature distribution which is desirable for any experimental verification of mathematical methods.

The use of a remotely controlled optical pyrometer having a very short response time and a spatial resolution at the surface of the blade of the order of mm^2, provides a solution to this problem.

A detailed description of the pyrometer developed by ONERA within the framework of the MINOS project is given in Ref.11. Two instruments of this type are installed on the MINOS test rig in order to record simultaneously the temperatures of the leading and trailing edge zones of the rotor blades. The minimum detectable temperature difference is less than 5^oC for a resolution of $2\ mm^2$ at the blade surface.

Note

(a) Optical pyrometers can also be used to observe nozzle guide vanes and, in particular, to record the surface temperature at locations where thermocouple equipment is easily damaged.

(b) Another interesting application is the determination of local rotor blade heat transfer coefficients using the technique described in section 4.3. For this application, the pyrometric solution offers the advantages of precision and of simplicity of operation. The heat transfer coefficients can be measured whether a gaseous film is present or not.

(c) Pyrometric measurements are equally suited to the characterisation of thermal cycles produced during the validation of laws of thermal fatigue damage.

4.5 Measurement of heat flux

The experimental determination of heat flux in an aerodynamically disturbed zone adjacent to the casing wall downstream of the rotor is carried out using an equilibrium fluxmeter developed by SNIAS[12].

The measurement of the temperature gradient in the sensor and the increase in the temperature of its cooling liquid makes it possible to obtain the heat flux by independent means.

4.6 Experimental study of film cooling

Wall film cooling efficiency is characterised by the relationship:

$$\eta = \frac{T_f - T_{pa}}{T_f - T_{ic}}$$

where T_f is the total temperature of the external flow;

T_{pa} is the adiabatic wall temperature or the apparent total temperature of the film;

T_{ic} is the stagnation temperature of the cooling air.

The adiabatic wall temperature is difficult to determine directly but the efficiency can nevertheless be derived from an analysis of the composition of the layer formed by the mixing of the film and the external flow by seeding with a detectable chemical species.

In fact, the conditions for which Reynold's analogy between mass transfer and energy transfer is valid are conveniently fulfilled in such a way that there is an equivalence between the efficiency previously defined and the efficiency defined by means of mass fractions, Γ_j , of a constituent j in the three flows considered[13];

$$\eta' = \frac{\Gamma_{g,j} - \Gamma_{p,j}}{\Gamma_{g,j} - \Gamma_{c,j}} .$$

The indices g, c and p correspond to the hot external gas flow, the cooling gas issuing from the emission channels and to the flow adjacent to the wall where one wishes to study the protective film respectively.

During turbine testing, the efficiency of the film can be characterised by analysis of the concentration of one of the constituents of the mainstream flow, for example CO_2 or O_2, since the composition of the vitiated air of the mainstream differs from the composition of the cooling air. Fig 3, taken from Ref 14, illustrates this equivalence of temperature measurement and of concentration measurements in a study of the efficiency of wall film cooling.

The samples taken are analysed by gas-phase chromatography.

5 TECHNOLOGICAL CONCEPT

The starting point of the technology study was the idea of using a hot turbine test rig available at CEPr.

On this rig, turbines may be coupled to hydraulic brakes and supplied with gas under pressure. A combustion chamber makes it possible to pre-heat the air and to re-create the desired turbine inlet temperature conditions.

The particular objectives of the MINOS project imposed restraints which led to the choice of the hardware described below.

5.1 Test objective constraints (Fig 4)

It was considered desirable to add an LP nozzle guide vane assembly to the HP stage, enabling the effect of the HP rotor wakes to be studied.

The guide vanes must be supplied with cooling air by independent circuits such that the flow may be varied over a wide range.

Certain nozzle guide vanes must have separate supplies, the flow to each vane being measured, and each must be equipped with a device to interrupt the flow so that the temperature of the metal can be measured in a transient manner.

The rotor must have a system of airtight labyrinth circuits in order to cut down leakages and to enable measurements to be taken, with adequate precision, of the flow of the coolant entering the rotor system.

For flow characterisation the spacing of guide vanes must be sufficiently large to permit the passage of measuring probes or pyrometers.

The overall structural assembly of the rig must be designed to support stresses corresponding to a turbine inlet temperature of 1800 K.

The installation of a rotating data collector is necessary for the transmission of measurements carried out on the rotor; bearing in mind the temperature levels anticipated, special cooling must be arranged for this collector and for the exhaust assembly structures.

5.2 Principle technological choices

Fig 5 shows the principle technological choices which have been made:

- the existing pre-heater, combustion chamber and shafting have been retained and the turbine rotor has been mounted in a cantilever fashion in order to ease dismantling;
- in spite of the distance between them, the bearings have been placed in a single enclosure around which thermal insulation has been arranged to avoid heating of the air-oil mixture;
- the supply of cooling air to the rotor is effected upstream and downstream for all or some of the blades with protective labyrinths on the downstream side only, which make it possible to measure the flow accurately;
- the LP nozzle guide vanes must be removed for certain tests, and hence supporting struts for the exhaust casing are introduced. These are cylindrical in order to withstand the variable incidence of the flow; they also provide air passages for rotor cooling and other cooling and pressurisation circuits.

6 THE MINOS TURBINE TEST FACILITY

6.1 The CEPr turbine test facility

This test facility was chosen for the MINOS project having regard to:

- the large air flows which can be provided;
- its suitability for tests at high temperatures;

- the joint experience acquired by SNECMA and CEPr using this test facility for the testing of engine turbines.

6.1.1 History

Constructed in 1965, the turbine test facility was first used to characterise the aerodynamic design of various versions of the ATAR and M45 turbines. In 1970, the operational capabilities were extended (particularly in respect of rotational speed and turbine inlet temperature). Thereafter tests on the M53 and CFM56 (first stage LP) turbines were concerned with the study of their aerodynamic design, the study of temperature distribution and work output, vibration characteristics and the validation of new technology by high temperature endurance testing.

6.1.2 Description of the test installation

The shaft system, capable of speeds up to 25000 rev/min, is coupled to two hydraulic brakes which can absorb a total power of 12000 kW.

The Test Centre plant can supply air to the test rig inlet volute at a pressure of 4.5 bar, a temperature of 620 K and a standard flow rate of 65 kp/s. By way of example, an operational condition frequently reproduced for turbines on the test bench is M = 2, Z = 18000 m.

A cannular pre-heater reproduces compressor temperature rise.

An engine combustion chamber assures the desired turbine inlet temperature.

Various sources of compressed air supply the ventilation circuits of the turbine (up to 20 in the case of MINOS).

6.1.3 Capacity of instrumentation system

The data acquisition system makes possible the simultaneous, or almost simultaneous, measurement of:

- 1250 parameters under steady state conditions;
- 128 parameters in a transient mode at a rate of 40 Hz;
- about 70 parameters are provided with an alarm.

6.2 Test procedure

The test procedure is characterised by its flexibility and by the complexity associated with the large number of test parameters which can be controlled (Fig 6):

- ambient conditions: inlet pressure, inlet temperature, exhaust pressure, these conditions being governed by the operational characteristics of the air supply plant, the circuits used and the control valves of the test rig;
- the torque absorbed by each of the brakes;
- the flow rate of each cooling air circuit;
- the flow rate of the fuel in the pre-heater and the combustion chamber.

The control system enables a wide variation of turbine related parameters: speed of rotation, air mass flow rate, temperature and pressure at inlet to the HP nozzle guide

vanes, the change in specific enthalpy, blowing ratios, cooling flow rates ... . This complexity, combined with a concern for efficiency leads to several experiments being carried out simultaneously, requiring the presence of numerous operators during a test.

6.3 Data acquisition and processing for MINOS

In a steady state mode, about 550 pressure measurements, 650 temperature measurements and other measurements of various kinds can be recorded and processed by the central IBM 1800 computer of CEPr. The data is reduced in real time by one of the nine software programmes developed to cover the scope of the MINOS tests.

In order to characterise the flow in the rig and to ensure control over the operation of the turbine, the pressure and temperature measurements are divided in the following way (Table 2).

Table 2

Purpose	Number of measurement channels	
	Pressure	Temperature
Characterisation of the flow in the different turbine measurement planes	210	90
External measurements; cooling air flow rate	70	20
Internal measurements:		
- guide vanes	160	375
- casings, internal cavities	100	180

Numerous bosses are provided in the various planes of measurement so that the test rig can be equipped with pressure and temperature probes or with other instrumentation.

In a transient mode, 120 temperature measurements, originating at the stator or rotor (with the aid of a rotating multiplexer) are processed by a MITRA 15 computer, providing visual display of the results in numerical or graphic form in the control room. The data acquired, mainly temperature measurements, are stored on magnetic tape and are processed in delayed time, in order to derive, for example, the local heat transfer coefficients of the NGVs and rotor blades.

Thirty-five vibration and stress measurements are permanently displayed visually on an oscilloscope and are recorded on magnetic tape.

Pyrometer readings are also displayed visually on the oscilloscope and recorded on analogue magnetic tape by means of a wide band pass recorder (500 kHz in IF). The processing of the data acquired is carried out in delayed time. The same method is used for the acquisition and processing of data supplied by non-steady pressure probes used in the analysis of rotor blade wakes.

A remotely controlled device withdraws gas samples for the study of film cooling effects. The samples taken are analysed in delayed time by gas-phase chromatography.

7 EXAMPLES OF RESULTS

The different tests carried out on the MINOS facility have produced numerous results which, on the one hand enabled the limits of validity of prediction methods to be established, and, on the other hand made it possible, in a typical engine environment, to characterise experimentally various phenomena which, up to then, had only been studied using static model test rigs.

In order to illustrate the capabilities of the MINOS test facility, four examples of the results obtained are presented below.

7.1 Pressure fluctuations - turbulence

The use of pressure probes with short response times has made it possible to characterise the aerodynamic turbulence of the flow at inlet to the HP nozzle guide vanes. A mean level of turbulence of the order of 9% has been recorded at the experimental operation point. The radial and circumferential heterogeneity of this parameter, observed at the test vanes, must be attributed to the geometry of the combustion chamber.

A comparison of the spectra of pressure fluctuations of the flow at different vane heights is shown in Fig 7. The fluctuations detected close to the outer casing are larger relative to those measured at mid-span. Certain dominant frequencies appear in the spectra; their origin is still ill-defined.

The examination of such experimental data is relevant to studies of turbulent flow in turbo machinery being carried out at numerous laboratories and to its influence upon various phenomena such as boundary layers and the film cooling efficiency of blades.

7.2 Nozzle guide vane heat transfer coefficients

The experimental distribution of heat transfer coefficient on the pressure and suction surfaces of the nozzle guide vanes with no film cooling is illustrated in Fig 8. It is compiled from numerous successive cycles (stopping and starting of internal cooling to the vanes) to minimise the errors associated with the scatter of temperature measurements.

The difficulty of fitting thermocouples sufficiently close to each other near the vane leading edge makes it impossible to accurately characterise the distribution of heat transfer coefficients in this zone. Optical pyrometry or other new methods of measurement should offer a solution to this problem. This study demonstrates the possibility of maintaining, on aerodynamically well-designed blades, a laminar flow over a high proportion of the profile, a condition favourable for cooling. In the case of the suction surface, quite good agreement is observed between the experimental distribution of heat transfer coefficient and that calculated by the method described in Ref 15. In the case of the pressure surface, calculation indicates a re-laminarisation of the boundary layer which the tests do not reveal.

Moreover, it seems that, in the particular case of MINOS, the engine environment does not appreciably modify the heat transfer coefficients relative to those found using static model tests.

7.3 Optical pyrometry on rotor blades

Fig 9 illustrates surface temperature profiles measured by optical pyrometry on the suction surface of a rotor blade for two cooling air flow rates.

This technique can be used to determine temperature gradients on the blade surfaces, especially in the vicinity of leading edges and around cooling holes, and to identify poorly cooled zones. In the example shown, the effect of cooling flow rate on the temperature at the edge of a cooling hole can be seen. The temperature contour plots thus established may then be used as a data base for validation of methods of predicting the efficiency of internal convection and film cooling systems.

7.4 Cooling the platforms of the HP nozzle guide vanes

The cooling of the platforms of the HP nozzle has been studied both for the case of film cooling from two rows of holes upstream of the platforms and, for the case of emission through perforations distributed over these same platforms.

In the first case, the efficiency of the protective film is derived from analyses of gas samples taken from numerous points on the platform surfaces. Fig 10 shows a section taken near the outer wall.

In the second case, the thermal iso-efficiencies have been derived from temperature measurements at the wall, carried out using thermocouples. The results obtained are presented in Fig 11.

8 CONCLUSIONS

The studies carried out using the MINOS test rig have demonstrated the flexibility of application of this type of testing. The ability to independently vary a large number of parameters has eased the analytical task.

The influence of an engine environment on heat transfer coefficients or on the efficiency of film cooling has been studied.

Correct operation of various instruments which had previously only been used for laboratory studies has been demonstrated on this rig. Detailed measurements carried out using this facility have made it possible to state that the prediction methods in use for determination of aerodynamic performance and thermal behaviour of gas turbines are valid.

The study programme currently being pursued should provide more detailed knowledge for the optimisation of blade cooling systems and should provide confirmation of the validity of methods used to predict their life.

In conclusion, the MINOS test rig appears to be an effective tool both for the gas turbine designer and for the research worker who, on the basis of results acquired using this facility, can specify supplementary tests on static test rigs with more confidence and refine prediction methods, making it possible by this means, to accelerate the development of gas turbines.

DISCUSSION

A.J.B. Jackson, UK:

To what temperature do you intend to develop and test the MINOS apparatus in the future, and what are the limitations to increasing the test temperatures?

Author's reply:

The MINOS test rig has been designed for a turbine inlet temperature of 1500°C and we do not, at present, envisage any increase in this temperature, since this would require considerable modifications.

Table 1

THE PLACE OF MINOS AS A TEST VEHICLE IN A PROGRAMME OF HIGH TEMPERATURE TURBINE RESEARCH

	Advantages	Disadvantages
Full-scale engine testing	Engine test conditions	Complexity and lack of flexibility of tests Interactions between parameters Difficulties in obtaining detailed measurements Difficulty in correlating results with other types of engine High cost
Scale model test rigs	Studies of the effects on overall performance of separate elements Relative simplicity of test installations Easy and rapid parametric study Variable test conditions Relatively moderate cost Conclusions directly applicable to engine development	Test conditions do not always accurately reproduce engine conditions Results often too universal to permit detailed analysis of elementary phenomena
Studies using simple apparatus	Detailed analysis of fundamental phenomena Refined and precise measurements carried out Close theory-experiment relationship Fundamental research: short, medium and long-term objectives	Test conditions sometimes far removed from those encountered in engines
Synthesis of fundamental research	Development of prediction methods for turbomachinery design	Difficulties in correlating prediction hypotheses with complex phenomena Difficulties in validating calculation methods under engine test conditions
MINOS experimental rig	Validation of performance and design prediction methods for high-temperature turbines in the presence of an engine environment Intermediate rig between model test rigs and engine testing (detailed measurements possible, flexibility of control of operating parameters) Close relationships with test engines, tests on model rigs and fundamental research	Technical constraints in the design of the test rig imposed by the measurements to be carried out Difficulties in equipping the test rig with instrumentation

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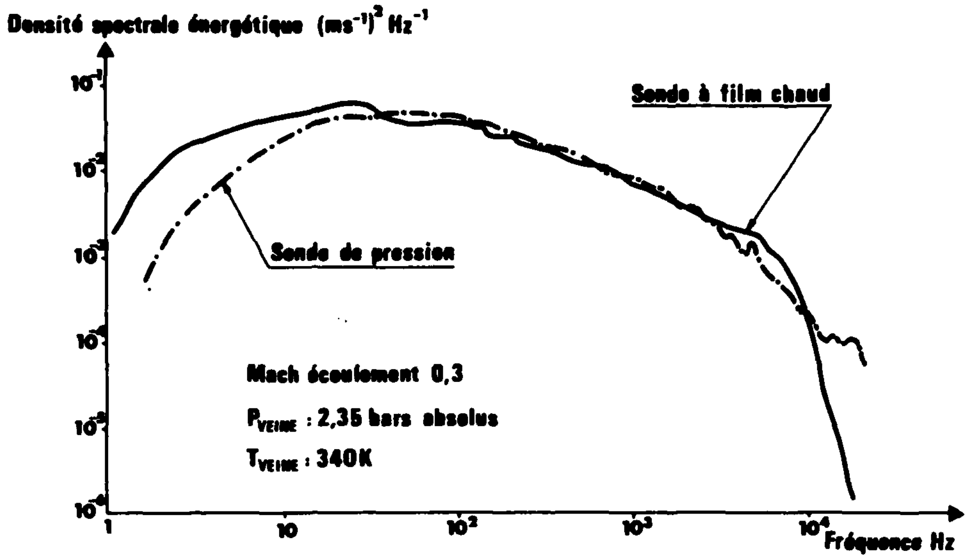
~~[illegible] ORGANISATIONS~~

Fig 1

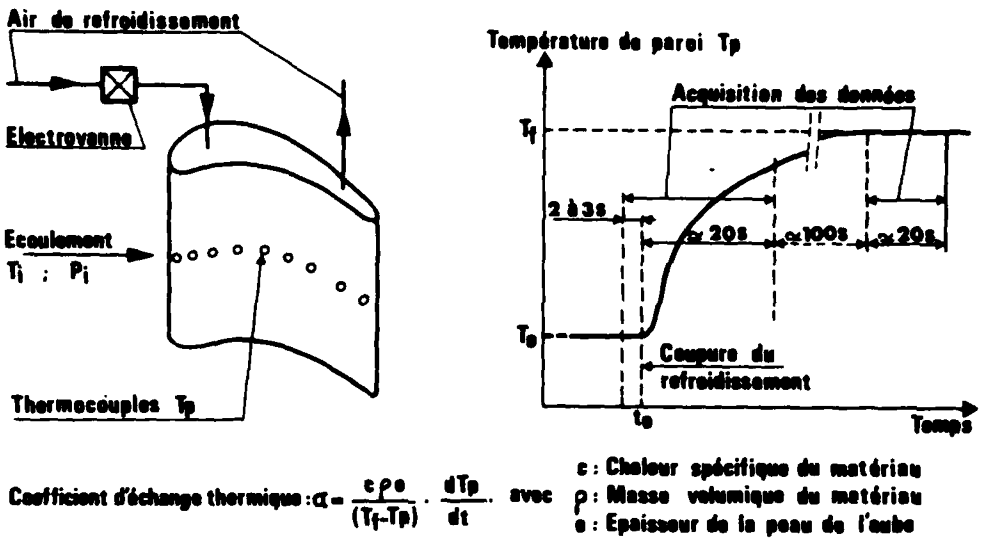


Key:
Abscissa: frequency, Hz
Ordinate: spectral energy density, $(ms^{-1})^2\ Hz^{-1}$

— · — · — pressure probe
———— hot wire probe

P_{vane} = 2.35 bar, absolute
T_{vane} = 340 K
Mach No. = 0.3

Fig 1 Spectral densities of velocity fluctuations; comparison of two types of probe



Key:

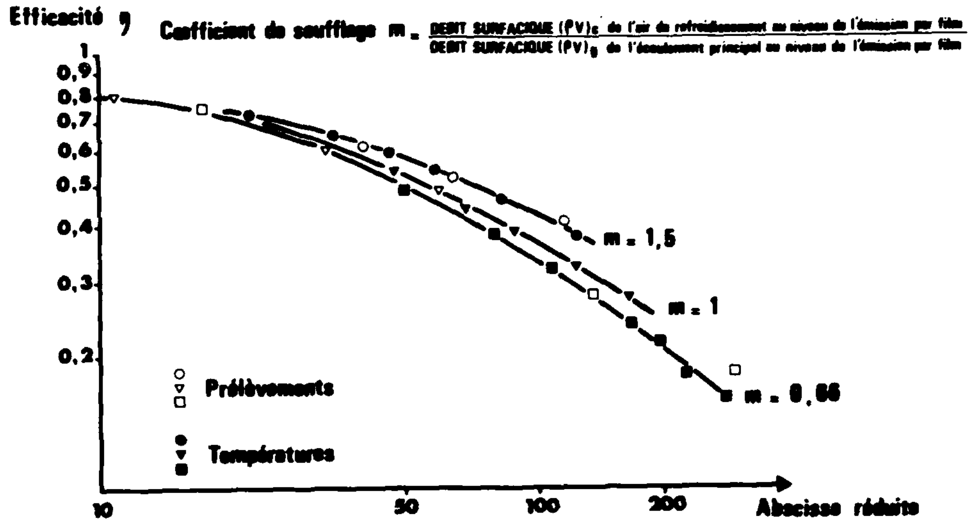
Air de refroidissement	cooling air
Electrovanne	solenoid valve
Ecoulement	flow
Température de paroi	wall temperature
Acquisition des données	data acquisition time
Coupure du refroidissement	coolant shut-off
Temps	time

Heat transfer coefficient: $\alpha = \frac{c\rho e}{(T_f - T_p)} \cdot \frac{dT_p}{dt}$

where c is the specific heat of the material
ρ is the density of the material
e is the thickness of the blade wall

Fig 2 Principle of measurement of the local heat transfer coefficient around nozzle guide vanes of the MINOS type

Fig 3



Key:
Abscissa is reduced
Ordinate: efficiency, η

○ ▽ □ } samples ● ▼ ■ } temperatures

$$\text{Blowing coefficient, } m = \frac{\text{surface flow rate } (\rho V)_c \text{ of cooling air at the point of film emission}}{\text{surface flow rate } (\rho V)_g \text{ of main flow at the point of film emission}}$$

Fig 3 Thermal efficiency of film cooling; comparison of temperature and gaseous concentration measurements

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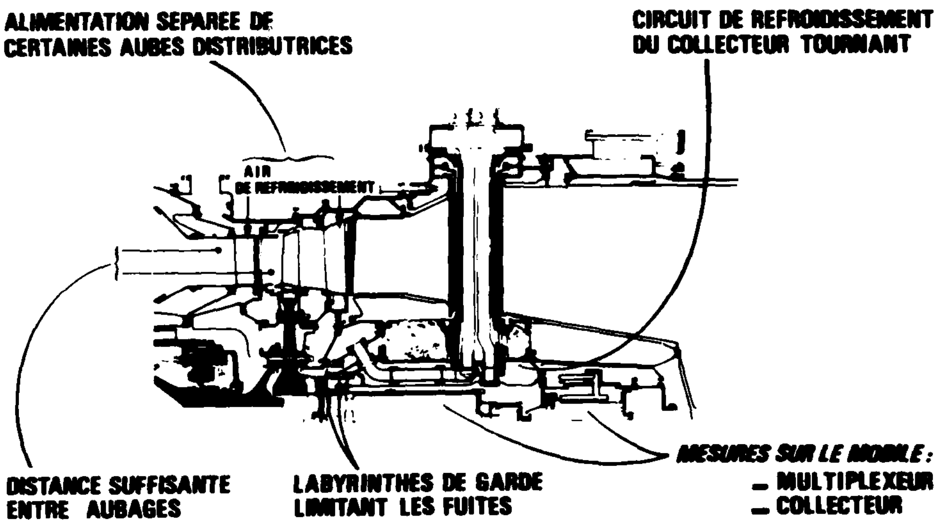
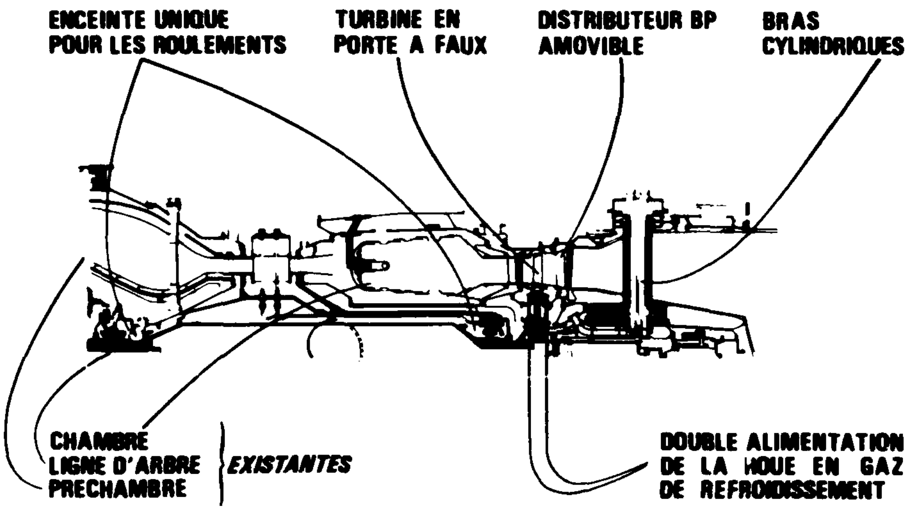


Key:

Alimentation separée de certaines aubes distributrices	separate supply to certain nozzle guide vanes
Circuit de refroidissement du collecteur tournant	cooling circuit for rotating data collector
Distance suffisante entre aubages	adequate distance between blading
Labyrinthes de garde limitant les fuites	protective labyrinths restricting leakages
Mesures sur le mobile	measurements on the rotor blade:
- multiplexeur	- multiplexer
- collecteur	- collector

Fig 4 Concept of test rig, displaying the measurements to be carried out

Fig 5



<u>Key</u>:

Enceinte unique pour les roulements	single enclosure for bearings
Turbine en porte à faux	cantilever mounted turbine
Distributeur BP amovible	LP nozzle removable
Bras cylindriques	cylindrical struts
Chambre, Ligne d'arbre, Préchambre } Existantes	existing { combustion chamber, shafting, pre-heater
Double alimentation de la roue en gaz de refroidissement	double supply of cooling gas to the rotor

Fig 5 Test rig design; main technological choices

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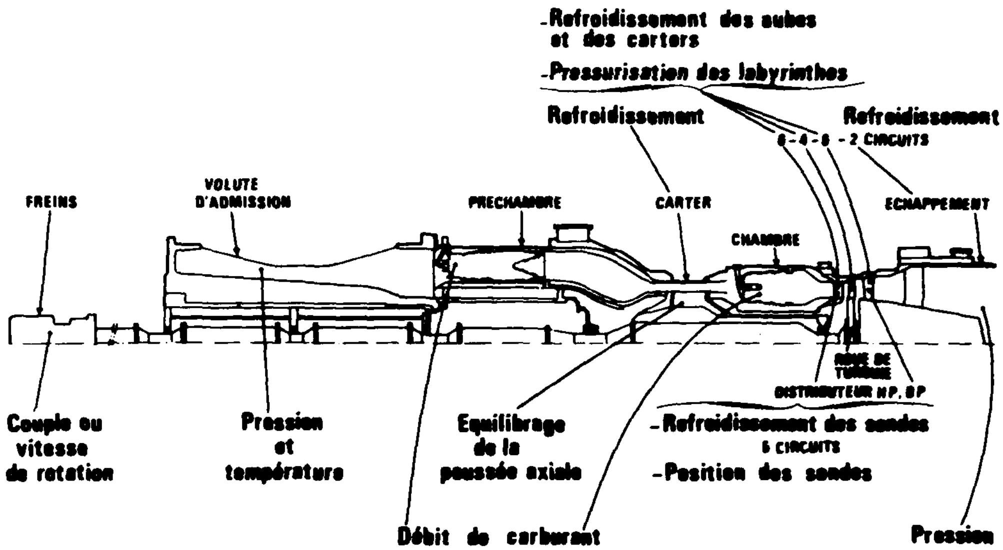
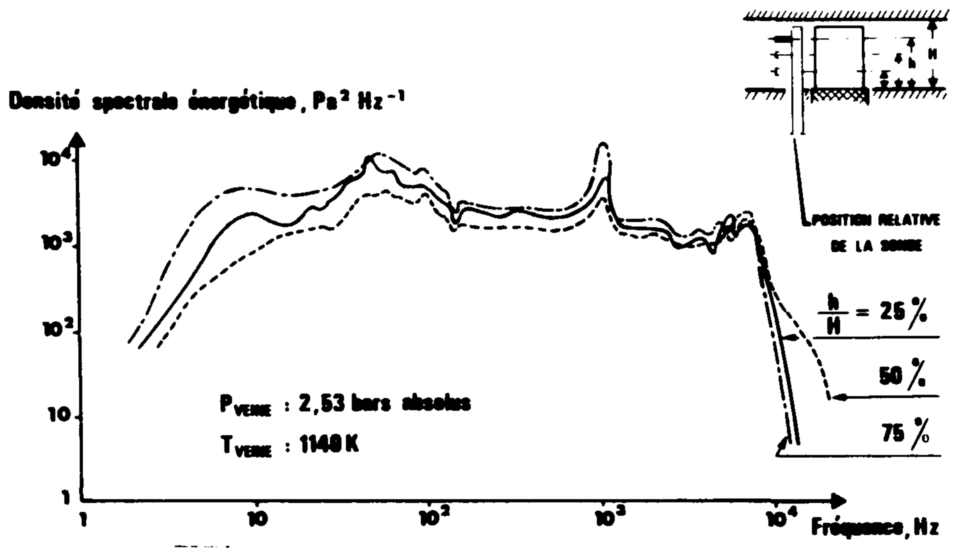


Key:	
Refroidissement des aubes et des carters	cooling of blades and casings
Pressurisation des labyrinthes	pressurisation of labyrinths
Freins	brakes
Volute d'admission	inlet volute
Prechambre	preheater
Refroidissement	cooling
Carter	casing
Chambre	combustion chamber
Echappement	exhaust
Pression	pressure
Roue de turbine	turbine disc
Distributeur HP, BP	HP, LP nozzles
Refroidissement des sondes	cooling of probes - 5 circuits
Position des sondes	position of probes
Equilibrage de la poussée axiale	balancing of the axial thrust
Pression et température	pressure and temperature
Couple ou vitesse de rotation	torque or speed of rotation
Débit de carburant	fuel flow rate

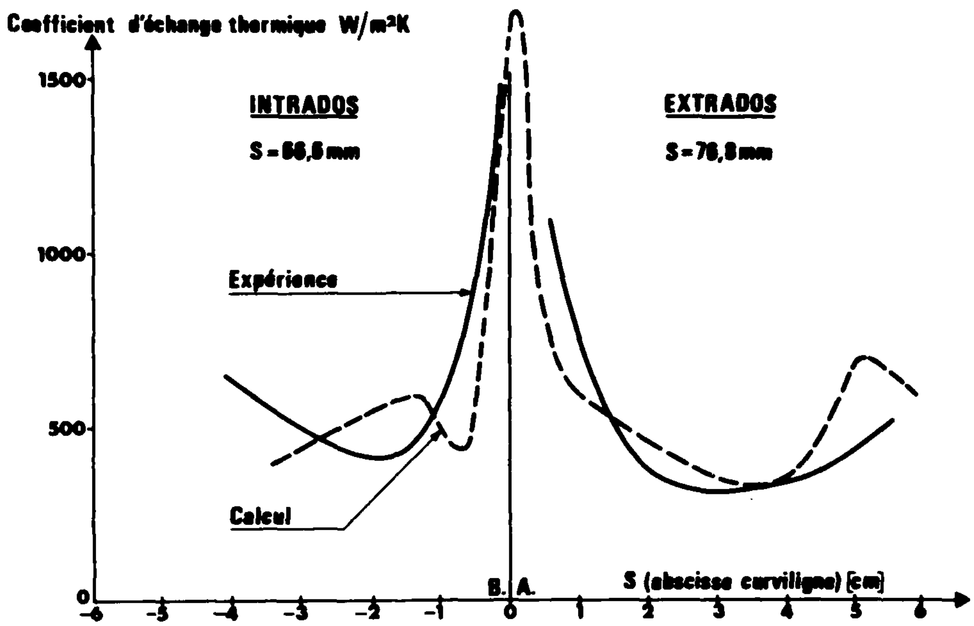
Fig 6 The MINOS on the CEP_r turbine test bench; control parameters

Fig 7



Key:
Abscissa frequency, Hz
Ordinate spectral energy density, $Pa^2\ Hz^{-1}$
P_{vane} = 2.53 bar, absolute
T_{vane} = 1140 K
Position relative de la sonde - relative position of the probe

Fig 7 Spectra of turbine inlet pressure fluctuations at different vane heights



Key:

——— experiment
------ calculation

S (abscisse curviligne) = abscissa curvilinear , cm

pressure surface: S = 66.6 mm
suction surface: S = 76.8 mm

Ordinate: heat transfer coefficient, $W\,m^{-2}\,K^{-1}$

Fig 8 Local heat transfer coefficient for the HP nozzle guide vanes

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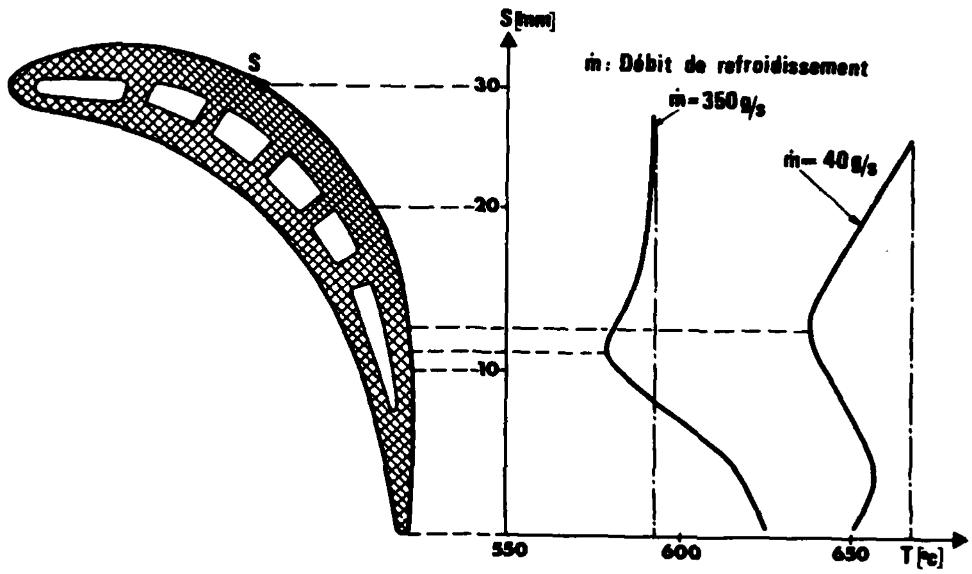
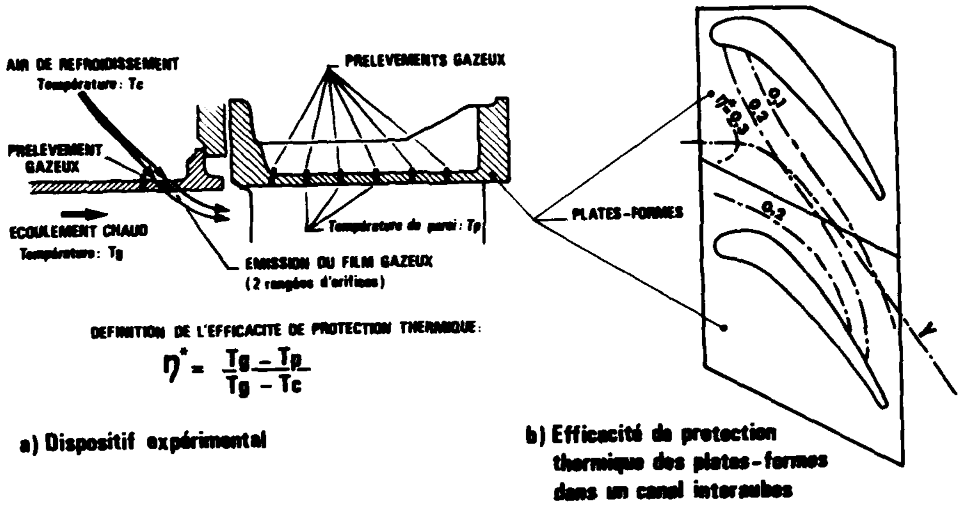
Fig 9



Key:
ṁ: Débit de refroidissement = cooling flow rate, ṁ

Fig 9 Influence of cooling on the temperature profile of the suction surface



Key:

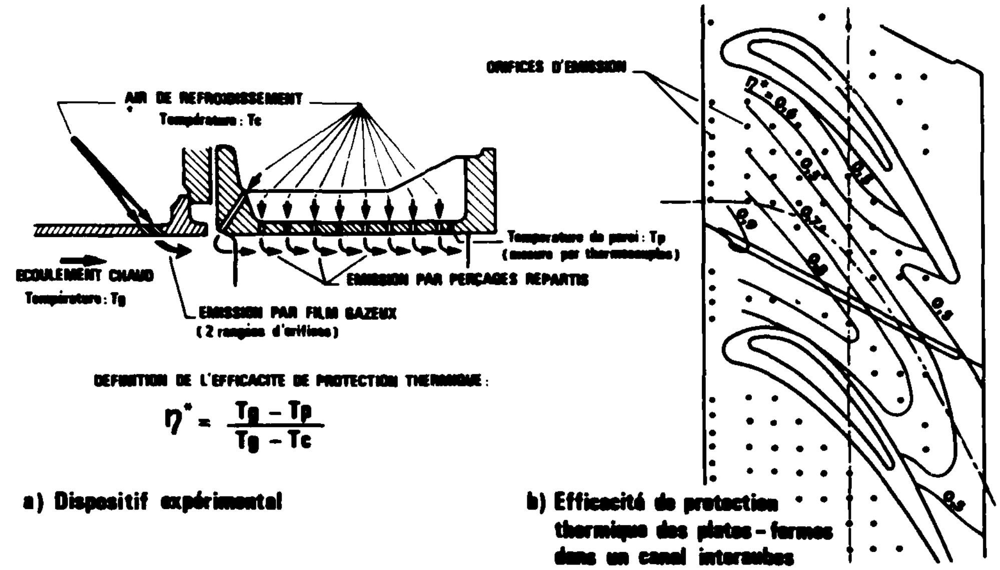
Air de refroidissement	cooling air; temperature, T_c
Prelevements gazeux	gas sampling points
Plates-formes	platforms
Température de paroi	wall temperature, T_p
Emission du film gazeux	emission of gaseous film (2 rows of holes)
Ecoulement chaud	hot flow; temperature, T_g

Definition of the efficiency of thermal protection: $\eta^* = \dfrac{T_g - T_p}{T_g - T_c}$

(a) Experimental arrangement

(b) Efficiency of platform thermal protection in an inter-vane passage

Fig 10 Thermal protection of HP nozzle guide vane platforms; the case of a gaseous film emitted by two rows of holes



Key:

Air de refroidissement	cooling air; temperature, T_c
Orifices d'emission	emission holes
Ecoulement chaud	hot flow; temperature, T_g
Emission par film gazeux	emission of gas film (2 rows of holes)
Emission par perçages repartis	emission through distributed perforations
Temperature de paroi	wall temperature, T_p (measurement by thermocouple)

Definition of the efficiency of thermal protection: $\eta^* = \dfrac{T_g - T_p}{T_g - T_c}$

(a) Experimental arrangement

(b) Efficiency of platform thermal protection in an inter-vane passage

Fig 11 Thermal protection of HP nozzle guide vane platforms; the case of a gaseous film emitted by distributed perforations

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